RADOMES

Dr. Ely Levine
Radome Structure and Properties

1. **Introduction:** Functions of the radome, electrical aspects, mechanical aspects, radome classifications.

2. **The Basic radome:** Reflection and transmission (half space), the single wall: reflection, transmission and insert phase, effects of wall thickness, thin and thick walls, graphical design aids.

3. **Sandwich radome:** Structure and performance.

4. **Shaped Redoes:** Effects of curvature and non uniform thickness.

5. **Effects of the radome on the Antenna properties:** Assumptions, radome effects: beam width, bore sight error, side lobes, gain, polarization, return loss and noise temperature, how to specify a radome ? radome measurements.

6. **radome Materials:** Materials in use, comments.

7. **References**
CHAPTER 1 - INTRODUCTION

Functions of the Radome

Electrical aspects

Mechanical aspects

Radome classifications
Functions of the radome

Many microwave / RF antennas require a housing, or radome (“RAdar DOME”) for one or more of the following requirements:

(1) Protection against weather including: temperature, humidity salt, sun radiation, wind, rain and icing
(2) Proper incorporation into the streamlined structure of an airborne / shipborne platform
(3) Provision for pressurizing
(4) Reduction of scanning power requirement (in lack of wind)
(5) Hiding the antenna for security reasons
Functions of the radome (cont)

radome Properties:

(1) Minimal impairment of the electrical performance of the antenna

(2) Made of low-loss dielectric materials which are shaped to cover the antenna and matches the aero-dynamical requirements

(3) Compatible with all mechanical and environmental characteristics
Functions of the radome (cont)

Locations of Redoes on Aircraft
Electrical Aspects

Redoes can cause some distortions of Electro-Magnetic waves radiated or received by the antenna

* Reduce Gain
* Change the Direction of the main beam
* Change Beam Width
* Enlarge Side Lobes
* Change Polarization
* Reflect waves into the transmitter
* Enlarge antenna Noise Temperature
Electrical Aspects (cont)

Perfect radome:

- Power Transmission \( \approx 100\% \)
- Power Reflection \( \approx 0\% \)
- Power Absorption \( \approx 0\% \)
- Insertion Phase \( \approx \) constant at all angles of incidence
- Impact on the antenna \( \rightarrow 0 \)
Electrical Aspects (cont)

Typical Radiation Pattern of Radar Antenna With and Without radome
Mechanical Aspects

- Limited choice of non metallic materials
- Appropriate strength, especially in airborne applications
- Stiffness, prevention of deformations
- Heating / cooling due to sun radiation and air flow
- Minimal absorption of water
- Minimal abrasion and erosion due to dust, sand, small stones, rain drops, hail impact, salt fog and bird impact
- Weight and center of gravity considerations
- De-icing or anti-icing
radome Classifications

A. By wall Thickness

For a single homogeneous layer with thickness $d$, we define:

$d \approx \lambda/2$ (resonant wall)

$d << \lambda/2$ (thin wall)

$d > \lambda/2$ (thick wall)
radome Classifications (cont)

Graphical Presentation Of Power Transmission through A Single Layer radome as a function of the radome Thickness
radome Classifications (cont)

B. By Layer structure

* Single Layer
* Sandwich (usually three layers)
* Multi Layer
radome Classifications (cont)

C. By Shape

* Planar or quasi-planar type
radome Classifications (cont)

* Curved:
  ** Normal incidence (0° - 30°): smoothly shaped or spherical or cylindrical radomes
  ** Streamlined (30° - 90°): ogive or ellipsoidal or conical radomes
radome Classifications (cont)

Planar and Shaped Redoes
CHAPTER 2 - THE BASIC RADOME

Reflection and Transmission (half space)
The single wall
Reflection, Transmission and insert phase
Effects of wall thickness
Thin and Thick walls
Graphical Design Aids
Reflection And Transmission (Half Space)

Consider a plane wave normally incident from free space (Ei) onto the surface of half space with $\varepsilon_r$, $\mu_r$ and $\sigma$. 

![Diagram of reflection and transmission](image)
Reflection And Transmission (Half Space) (cont)

Assume that for \( z > 0 \) the region is a loss-less dielectric \( \mu_r = 1 \) and \( \sigma = 0 \).

The propagation constant in air is \( \gamma_0 = j \omega \) and in matter is \( \gamma = j \omega \sqrt{\epsilon_r} \).

The wave impedance in air is \( \eta_0 = 120 \pi \) and in matter is \( \eta = \eta_0 / \sqrt{\epsilon_r} \).

A reflected wave \( E_r \) has a reflection coefficient: \( \Gamma = (\eta - \eta_0) / (\eta + \eta_0) \).

A transmitted wave \( E_t \) has a transmission coefficient: \( T = 2 \eta / (\eta + \eta_0) \).
Reflection And Transmission (Half Space) (cont)

Consider now a plane wave obliquely incident on a planar interface between two dielectric layers.

The electric field is either in the XZ plane (parallel polarization) or normal to the XZ plane (perpendicular polarization) or some combination.
The angles of the waves are:

\( \theta_i \) (incident)

\( \theta_r \) (reflected)

\( \theta_t \) (transmitted)

The Law of Snell dictates that: \( \theta_i = \theta_r \) and

\( k_1 \sin \theta_i = k_1 \sin \theta_r = k_2 \sin \theta_t \)

where \( k_1 = \omega \) and \( k_2 = \omega \sqrt{\varepsilon_r} \)
Reflection And Transmission (Half Space) (cont)

The specific expressions for the reflection and the transmission coefficients are:

Parallel polarization:
\[
\Gamma = \frac{\eta_2 \cos \theta_t - \eta_1 \cos \theta_i}{\eta_2 \cos \theta_t + \eta_1 \cos \theta_i}
\]
\[
T = \frac{2 \eta_2 \cos \theta_i}{\eta_2 \cos \theta_t + \eta_1 \cos \theta_i}
\]

Perpendicular polarization:
\[
\Gamma = \frac{\eta_2 \cos \theta_i - \eta_1 \cos \theta_t}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_t}
\]
\[
T = \frac{2 \eta_2 \cos \theta_i}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_t}
\]
Reflection And Transmission (Half Space) (cont)

Calculated example of $\Gamma$ ($\varepsilon_r = 2.55$) shows the difference between the two polarizations.

In radome design the typical polarization is parallel.
The Single Wall

Consider a plane wave incident onto a single dielectric wall whose thickness is $d$, the dielectric constant is $\varepsilon_r$ and the loss tangent is $\tan\delta$ ($\tan\delta << 1$).
The Single Wall (cont)

The calculation of the reflection and the transmission requires to sum all multiple reflections at both interfaces (known as “Fresnel” technique).
The Single Wall

The calculation of the reflection and the transmission requires to sum all multiple reflections at both interfaces (known as “Fresnel” technique). The results are presented here according to A. F. Kay notations.

\[ \phi = \left( \frac{2\pi d}{\lambda} \right) (\varepsilon_r - \sin^2 \theta_i) \]

where:
- \( \phi \) is the optical path length (radian)
- \( d \) is physical thickness (cm)
- \( \lambda \) is wavelength (cm)
- \( \theta_i \) is the angle of incidence (will be written from now on as \( \theta \)
Define now a parameter of attenuation due to dielectric losses:

$$L_0 = \varepsilon_r \tan \delta / 2(\varepsilon_r - \sin^2 \theta)$$

and an interface reflection coefficient (Fresnel coefficient):

$$r = (1 - \sqrt{\varepsilon_e} + jL_1) / (1 + \sqrt{\varepsilon_e} - jL_1)$$

where:

$$\varepsilon_e = (\varepsilon_r - \sin^2 \theta) / \cos^2 \theta \quad \text{for perpendicular polarization}$$

$$\varepsilon_e = (\varepsilon_r \cos^2 \theta) / (\varepsilon_r - \sin^2 \theta) \quad \text{for parallel polarization}$$
The Single Wall

And:  \( L_1 = (\varepsilon_r \tan\delta) / [2 \cos \theta \sqrt{\varepsilon_r - \sin^2 \theta}] \)  

\[ L_1 = (\varepsilon_r \tan\delta) \cos \theta [\varepsilon_r - 2 \sin^2 \theta] / [2 \sqrt{\varepsilon_r - \sin^2 \theta}] \]  

(parallel)

Finally we get:

\[ \Gamma = r[1 - \exp(-2\phi Lo - 2j\phi)] / [1 - r^2\exp(-2\phi Lo - 2j\phi)] \]  

(perpendicular)

\[ T = (1 - r^2) \exp(-\phi Lo - j\phi)] / [1 - r^2\exp(-2\phi Lo - 2j\phi)] \]  

(parallel)
Effective dielectric constant $\varepsilon_e$ as a function of the angle of incidence

Perpendicular Polarization

Parallel Polarization
Power reflection coefficient of a loss-less dielectric wall at normal incidence
Contours of constant power reflection (perpendicular polarization, $\varepsilon_r = 2.7$)
Contours of constant power reflection (parallel polarization, $\varepsilon_r = 2.7$)
The Insert Phase is a quantity of interest in radome phase distortion considerations and is given by:

\[ \Phi = \arctan (A \tan \phi) - 2\pi d \cos \theta / \lambda \]

where \( A = \frac{1 + r^2}{1 - r^2} \)

The factor \( A \) is a correction which takes into account of multiple reflections between the interfaces of the panel.
Insert phase as a function of the dielectric constant and incidence angle (d=0.5λ)
The Insert Phase is not a smooth function of thickness and angle of incidence. For normal-incidence radomes this is a minor problem. For highly curved radomes and wide scan antenna the Insert Phase should be carefully optimized.

Perpendicular polarization ($\varepsilon_r=6$)  
Parallel polarization ($\varepsilon_r=6$)
The Insert Phase is not a smooth function of thickness and angle of incidence. For normal-incidence radomes this is a minor problem. For highly curved radomes and wide scan antenna the Insert Phase should be carefully optimized.

Perpendicular polarization ($\varepsilon_r=2$)  
Parallel polarization ($\varepsilon_r=2$)
Graphical Design Aids

Classical graphs provide visual observations for the effects of the radome thickness and choice of materials.

For long wavelengths it is obvious that thin radomes (d < 0.1λ) are preferred.

For short wavelength the optimal radome has a thickness of \( d = 0.5 \frac{\lambda}{\sqrt{\varepsilon_r}} \)

The loss tangent should be selected to be minimal (\( \tan\delta < 0.01 \)).
Maximal thickness (Thin radome) as a function of incidence angle and $\varepsilon_r$.
Full line is 95% power transmission and dashed line is 90% power transmission.
Transmission loss of **half wavelength radome** as a function of $\tan \delta$.
Reflection as a function of the thickness for different values of $\tan\delta$.

3. The reflection characteristics at a plane-wall radome are shown as a function of sheet thickness.
Transmission as a function of radome thickness for different values of tanδ
EXAMPLE: Power Transmission of flat panels at 9.375 GHz

\( \varepsilon_r = 5.5, \tan \delta = 0.0003 \quad \text{and} \quad \varepsilon_r = 3.2, \tan \delta = 0.015 \)

- **perpendicular**
- **parallel**
CHAPTER 3 - SANDWICH RADOMES

Structure

Performance
Structure

A common design (called A-sandwich) consists of two thin layers, or skins, having high dielectric constant ($\alpha$), spaced by a third low dielectric constant ($\beta$) layer called a core. The core thickness is usually $\lambda/4$ to cancel reflections.

A-sandwich walls are light and broadband and provide better transmission and reflections performance than the single wall designs. In rare cases the skins are not identical. There are also some radomes with made of multi layers.
A-Sandwich design case 1:

Performance:

**DATA:**
- Skin Dielectric Constant: \(4\varepsilon_0\)
- Core Dielectric Constant: \(1.2\varepsilon_0\)
- Skin Thickness: \(0.020\) in.
- Core Thickness: \(0.051\) in.
- Skin Loss Tangent: \(0.02\)
- Core Loss Tangent: \(0.005\)
- Design Angle: \(70^\circ\)
- Wavelength: \(3.2\) cm
Performance

A-Sandwich design case 2:
Performance

A-Sandwich design case 3:
Performance

A-Sandwich design case 4:
A-Sandwich design case 5:

Skins $\varepsilon_r=3.2$, $\tan\delta=0.015$, 0.9 mm

Core $\varepsilon_r=1.1$, $\tan\delta=0.005$, 6.4 mm

(a) Perpendicular polarization

(b) Parallel polarization
A-Sandwich design case 6:
Skins $\varepsilon_r=2.85$, $\tan\delta=0.003$
Core $\varepsilon_r=1.14$, $\tan\delta=0.004$
(a) skins = 1 mm
core = 7.6 mm
(b) skins = 1 & 0.2 mm
core = 7.6 mm
CHAPTER 4 - SHAPED RADOMES

Effects of Curvature

Non uniform thickness
Effects Of Curvature

In the streamlined radome the variation of incident angle and polarization angle causes pattern distortions of all types (beam widening, gain reduction, beam squint, enlarge side lobes, rotate polarization etc. The situation is much more severe if the antenna is scanned.

The EM wave-front suffers from refraction, guided wave excitation and scattering from tips and sharp edges. All these effects are very difficult for simulations and measurements.
Effects Of Curvature

* Multiple reflections
* Refraction
* Guided waves
* Scattering
Effects Of Curvature

CURVATURE OPTIONS:
radome#3 gave the minimal bore-sight error
Effects Of Curvature

Multiple internal reflections inside a curved panel
Effects Of Curvature

a) Extreme grazing angles in a conical radome with 30° vertex

b) Extreme polarization angles in a conical radome

VERTICAL PLANE DISH LOOKING DOWN
PURE PERPENDICULAR POLARIZATION
\( \alpha = 90^\circ \)

HORIZONTAL PLANE DISH LOOKING TO SIDE
PURE PARALLEL POLARIZATION \( \alpha = 0^\circ \)
Effects Of Curvature

EXAMPLE

Near field in presence of Highly shaped radome

Axis of sensing is orthogonal to the radiation axis of The antenna
Non Uniform Wall

a) Refraction of half wave radomes due to radius of Curvature $r/\lambda$ in wavelengths

b) Refraction due to taper $\gamma$ in radome wall
CHAPTER 5 - EFFECTS OF RADOMES ON THE ANTENNA

Assumptions
radome Effects
  Beam Width
  Bore Sight error
  Side Lobes
  Gain
  Polarization
  Return Loss
  Noise Temperature
How to specify a radome?
radome measurements
Assumptions

(1) Consider airborne radomes at high frequency
(2) Consider low loss materials at close-to-normal incident angles
(3) Consider parallel polarization (linear or circular)
(4) Consider medium-to-high gain antenna (transmit and receive)
(5) Consider well matched antenna
**radome Effects**

* Radiation Patterns in presence of the radome are not changed much
* Beam Width is almost the same (aperture is not changed)
* Bore Sight error is negligible (exists only if the radome is highly curved)
* Side Lobes are enlarged by few dB
* Gain is reduced by 0.5 dB to 1.5 dB (“Transmission Loss”)
* Polarization is shifted by few degrees (“Polarization Loss”)
* Return Loss is enlarged by few dB
* Noise Temperature is enlarged (detector sensitivity is reduced by 1-2 dB)
How To Specify A radome?

**Electrical Requirements:**

(1) Frequency and Bandwidth
(2) Transmission Loss at different pointing angles of the antenna
(3) Impact on radiation properties of the antenna: Gain, Beam Width, Beam Squint, Side Lobes, Polarization shift
(4) Impact on the antenna matching: Reflected power into the antenna, change of VSWR of the antenna
How To Specify A radome ?

Mechanical Requirements:
(1) Weight and Center of Gravity
(2) Aerodynamics and Air Loads
(3) Stress and Stiffness
(4) Shock and Vibrations
(5) Pressure / Altitude
(6) Special Finish / Paint
(7) Interfaces
(8) Reliability
How To Specify A radome?

Environmental Requirements:
(1) Thermal Exposure
(2) Sun Radiation including UV
(3) Humidity
(4) Dust / Sand
(5) Rain / Hail Impact
(6) Salt / Fog
(7) Icing
(8) Acoustic Noise
radome Measurements

(1) Dielectric Material electrical testing (measurements of Dielectric Constant Loss Tangent)
(2) radome Measurements. First we measure the main beam of the antenna without the radome and then we measure in presence of the radome. Transmission Efficiency is expressed in percent (%) and Transmission Loss is expressed in dB.
radome Measurements

(3) radome Boresight shift. The angular difference in the main beam caused by the radome.

Ceramic 0.5\( \lambda \) radome
Base 12\( \lambda \), Length 24\( \lambda \),
Source: Tricoles
(4) Antenna Pattern distortions (mainly impact on side Lobes).

Source: Wojtkowiak

6. These displays show the effects of flexible radomes on antenna performance at 6.4 and 33.4 GHz.
radome Measurements

(5) radome reflectivity or Return Loss of the antenna in presence of the radome.

Source: Wojtkowiak

A microwave antenna with and without a radome was evaluated at a center frequency of about 22.4 GHz.
CHAPTER 6 - RADOME MATERIALS

Materials in use

Comments
## Dielectric Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Frequency</th>
<th>$\varepsilon_r$</th>
<th>$\tan \delta$ (25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina (99.5%)</td>
<td>10 GHz</td>
<td>9.5–10.</td>
<td>0.0003</td>
</tr>
<tr>
<td>Barium tetratitanate</td>
<td>6 GHz</td>
<td>37 ± 5%</td>
<td>0.0005</td>
</tr>
<tr>
<td>Beeswax</td>
<td>10 GHz</td>
<td>2.35</td>
<td>0.005</td>
</tr>
<tr>
<td>Beryllia</td>
<td>10 GHz</td>
<td>6.4</td>
<td>0.0003</td>
</tr>
<tr>
<td>Ceramic (A-35)</td>
<td>3 GHz</td>
<td>5.60</td>
<td>0.0041</td>
</tr>
<tr>
<td>Fused quartz</td>
<td>10 GHz</td>
<td>3.78</td>
<td>0.0001</td>
</tr>
<tr>
<td>Gallium arsenido</td>
<td>10 GHz</td>
<td>13</td>
<td>0.006</td>
</tr>
<tr>
<td>Glass (pyrex)</td>
<td>3 GHz</td>
<td>4.823</td>
<td>0.0054</td>
</tr>
<tr>
<td>Glazed ceramic</td>
<td>10 GHz</td>
<td>7.2</td>
<td>0.005</td>
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<tr>
<td>Lucite</td>
<td>10 GHz</td>
<td>2.56</td>
<td>0.012</td>
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<tr>
<td>Nylon (610)</td>
<td>3 GHz</td>
<td>2.84</td>
<td>0.0002</td>
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<tr>
<td>Paraffin</td>
<td>10 GHz</td>
<td>2.24</td>
<td>0.0057</td>
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<tr>
<td>Plexiglass</td>
<td>3 GHz</td>
<td>2.60</td>
<td>0.0004</td>
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<tr>
<td>Polystyrene</td>
<td>10 GHz</td>
<td>2.54</td>
<td>0.00033</td>
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<tr>
<td>Porcelain (dry process)</td>
<td>100 MHz</td>
<td>5.04</td>
<td>0.0078</td>
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<td>Rexolite (1422)</td>
<td>3 GHz</td>
<td>2.54</td>
<td>0.00048</td>
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<tr>
<td>Silicon</td>
<td>10 GHz</td>
<td>11.9</td>
<td>0.004</td>
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<tr>
<td>Styrofoam (103.7)</td>
<td>3 GHz</td>
<td>1.03</td>
<td>0.0001</td>
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<tr>
<td>Telton</td>
<td>10 GHz</td>
<td>2.08</td>
<td>0.0004</td>
</tr>
<tr>
<td>Titania (D-100)</td>
<td>6 GHz</td>
<td>96 ± 5%</td>
<td>0.001</td>
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<tr>
<td>Vaseline</td>
<td>10 GHz</td>
<td>2.16</td>
<td>0.001</td>
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<tr>
<td>Water (distilled)</td>
<td>3 GHz</td>
<td>76.7</td>
<td>0.157</td>
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Source: POZAR
## Typical radome Materials

### Reinforced Thermo-set Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>dielectric constant</th>
<th>Loss Tangent</th>
</tr>
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<tbody>
<tr>
<td>Polyester / “E” Fiberglass</td>
<td>4.3</td>
<td>0.016</td>
</tr>
<tr>
<td>Epoxy / “E” Fiberglass</td>
<td>4.2</td>
<td>0.015</td>
</tr>
<tr>
<td>Epoxy / Quartz</td>
<td>3.5</td>
<td>0.015</td>
</tr>
<tr>
<td>Cyanate Ester / Quartz</td>
<td>3.3</td>
<td>0.003</td>
</tr>
<tr>
<td>Bismaleimide / Quartz</td>
<td>3.3</td>
<td>0.003</td>
</tr>
<tr>
<td>Polyimide / “E” Fiberglass</td>
<td>4.1</td>
<td>0.004</td>
</tr>
<tr>
<td>Polyimide / Quartz</td>
<td>3.1</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Source: www.nurad.com
### Typical radome Materials

#### Unfilled Thermo-plastics

<table>
<thead>
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<th>Material</th>
<th>Dielectric Constant</th>
<th>Loss Tangent</th>
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</thead>
<tbody>
<tr>
<td>PEEK</td>
<td>3.5</td>
<td>0.004</td>
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<td>PPO</td>
<td>2.6</td>
<td>0.0007</td>
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<tr>
<td>PEI</td>
<td>3.1</td>
<td>0.002</td>
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<tr>
<td>PES</td>
<td>3.0</td>
<td>0.001</td>
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<tr>
<td>ABS</td>
<td>2.8</td>
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<tr>
<td>PTFE</td>
<td>2.0</td>
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<tr>
<td>HDPE</td>
<td>2.3</td>
<td>0.0003</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>3.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>2.5</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

Source: www.nurad.com
Typical radome Materials

Rain Erosion Coatings

<table>
<thead>
<tr>
<th>Material</th>
<th>dielectric constant</th>
<th>Loss Tangent</th>
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<tbody>
<tr>
<td>Polyurethane Rain Erosion</td>
<td>3.75</td>
<td>0.06</td>
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<tr>
<td>Fluoro-elastomer Rain Erosion</td>
<td>3.0</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Source: www.nurad.com
Comments

(1) First selection is thin or thick radome. At frequencies of 10-20 GHz a $\lambda/2$ solid laminate is the natural choice. A thick sandwich type made of composite materials may also be considered.

(2) For narrow beam radars (with scanning) the radome structure and shape are extremely important. Special reinforced plastics with fiber matrix are highly recommended. Loss Tangent < 0.004.

(3) For broad-beam sensors, EW systems and communications links the mechanical aspects are dominant. Loss Tangent < 0.02.
7. REFERENCES

1. C.A. Balanis, Antenna Theory, Wiley InterScience, 2005.